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The Leonids: Is There Still A Threat?

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Brief Overview of the Leonids

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- Occur in mid-November of each year; debris from Comet Tempel-Tuttle (33 year period). Speeds of 71 km s^{-1}.
- Meteor storms in 1799, 1833, 1866, 1966, and 1999.
- Storms did not materialize in 1899 or in 1932 - Astronomers thought that Leonid storms were 18th-19th century events.
- Leonids roared back in 1966, reaching rates of ~100,000 per hour in greatest meteor display ever recorded.

1998 & 1999 Leonid Overview

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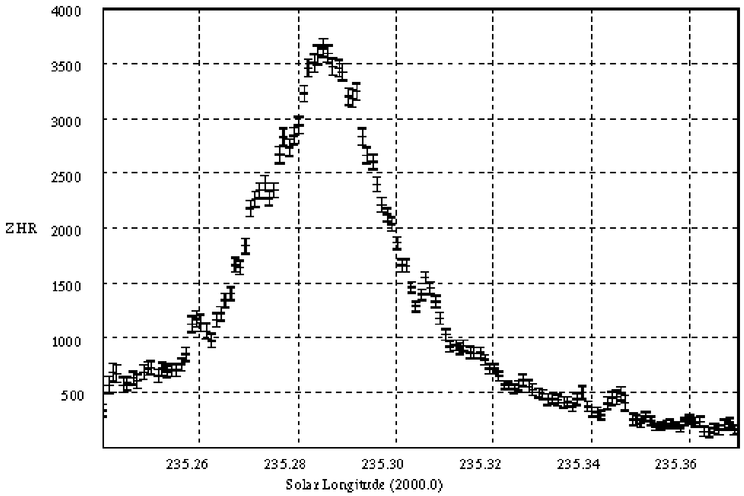
- 1998 saw an enhanced shower (ZHR ~350); 1999 witnessed a modest storm (ZHR ~3700).
- Storm in 1999 lasted about 45 minutes, rates peaked near predicted time at about 8:05 PM CST on November 17 .
- Over 2700 Leonids digitized from Israel tapes – 1200 analyzed.
- 200 spectra obtained in 1999.



- ALTAIR radar observed Leonid head echoes, decelerations may be obtained.

Historical Input

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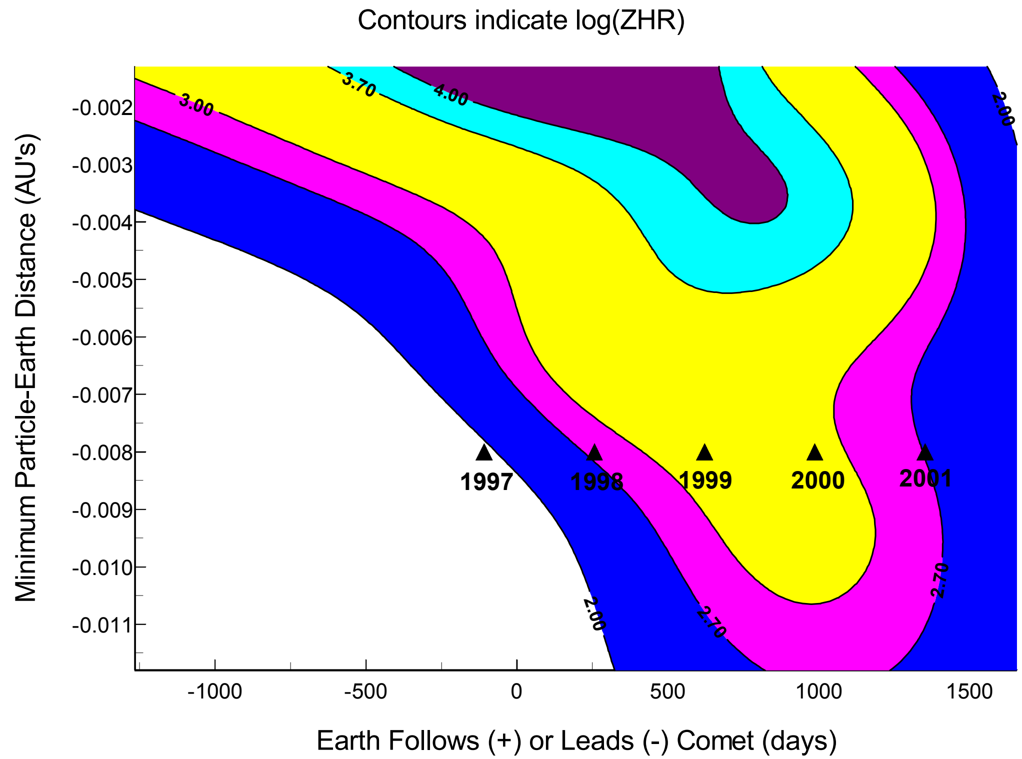
- Data from Yeomans (JPL), Mason, Jenniskens and Brown were combined to estimate the probability of storm and the ZHR for a given year:

Year	P_{storm}	ZHR
1998	0.6	550
1999	1.0	1400
2000	0.25	?
2001	> 0.3	?



Dynamical Models

- Primary ones recommended for consideration are those of David Asher and Peter Brown – others such as those of Wu and Lyytinen can be rejected because of failure to model past activity or use of non-standard assumptions (particles orbit comet rather than ejected from it).
- Both models make unphysical assumptions or approximations:
  - Asher ejects all particles at perihelion or at a constant rate, and ignores out of plane dispersal.
  - Brown ejects same number of particles, regardless of mass (corrects for this in post-analysis)…
- Asher's models seem to match observed times of peak better than Brown's (3-4 minute difference as opposed to 15).
- Both models do not match observed shower intensity.

The Leonids According to Asher

Date	Peak Time (UT)	Ejection Year	ZHR_{obs}
2000 Nov. 18	03:44	1733	30
	07:51	1866	20
2001 Nov. 18	10:01	1767	1500
	17:31	1699	15000
	18:19	1866	15000
2002 Nov. 19	04:00	1767	15000
	10:36	1866	25000

Predicted Circumstances - Asher

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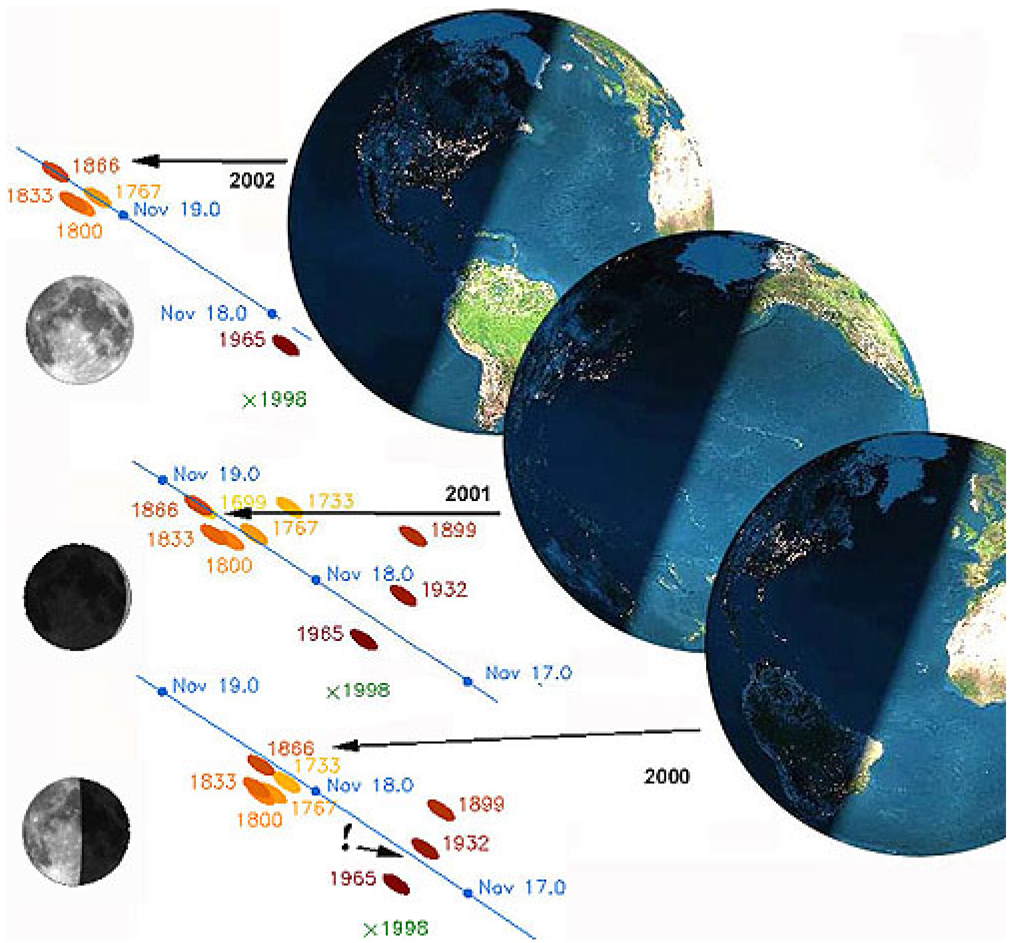
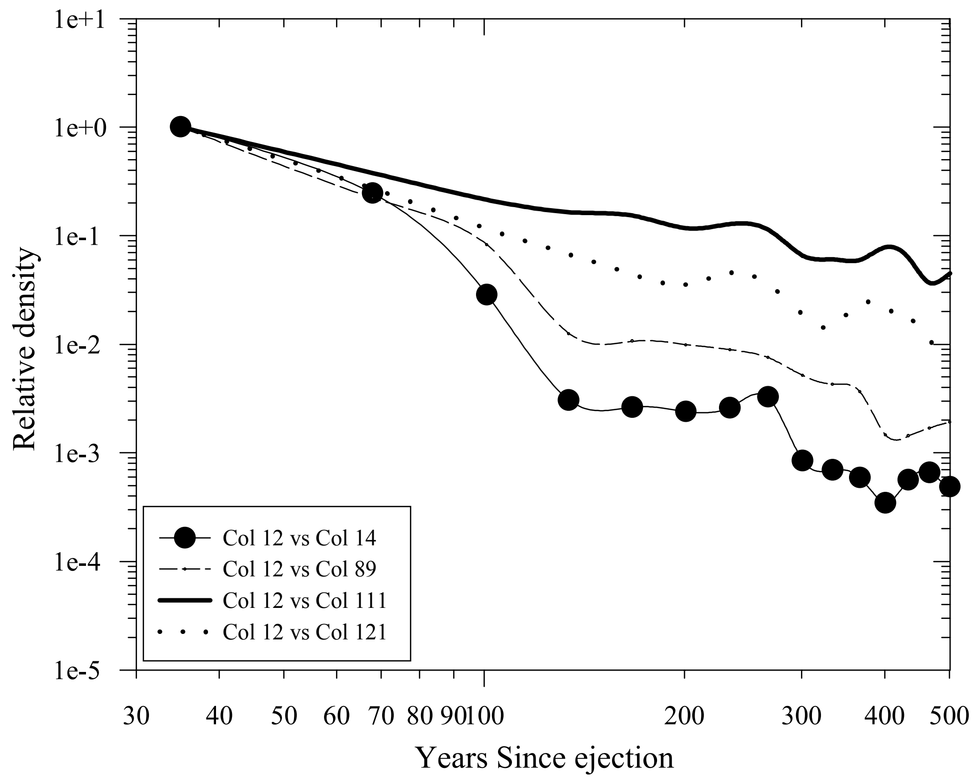


Graphic by P. Jenniskens and D. Asher

The Leonids According to Brown

- Leonid streams disperse over time as a result of perturbations (Poynting-Robertson drag, radiation pressure, etc.) – smaller particles affected more than larger ones (older streams have higher percentage of big particles and hence more bright Leonids).



Graphic by P. Brown

Leonids According to Brown - 2

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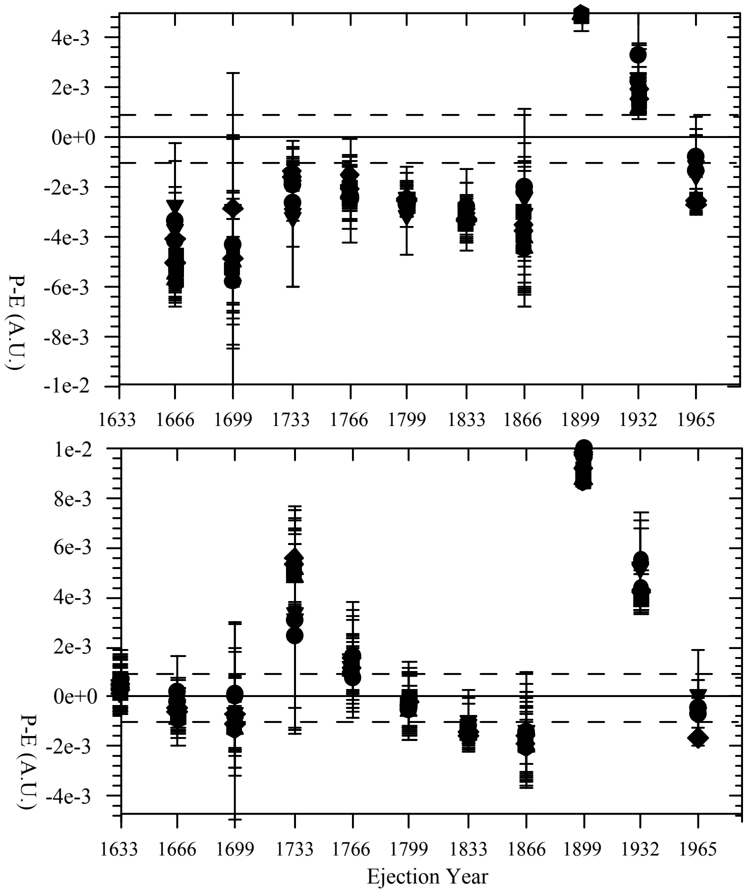

2000

2001

Computations give closest approach of particles to Earth during week of shower for various years of ejection…

Graphic by P. Brown

Solid line – Earth's position **Dashed line – Chandra apogee**

Cooke Interpretation of Brown

- Take average of all model distances for each stream.
- Perform logarithmic fit to Brown relative stream density over time.
- Scale 1899 density to match observed 1999 ZHR, assuming a gaussian with a dispersion given by Brown equation in 1999 paper[1] and a maximum ZHR of 10^5 at stream center.
- Apply logarithmic fit to deduce ZHRs at stream centers for other ejection years.
- Compute contribution to ZHR by each stream (also assumed gaussian in shape) using average distance, age, and ZHR at stream center.
- Only works for 2000 and 2001 (2002 not published).

[1]The Leonid Meteor Shower: Historical Visual Observations, *Icarus*, **138**, 287-308

Assumptions and Equations

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- Stream ZHR (density) profile is gaussian.
- ZHR at center of 1899 stream in 1999 was 10^5. 1899 stream center located at 0.0008 AUs from Earth.
- Eyeball fit of Figure 6.25 in Brown's dissertation:

$$\text{Log}\,(\text{density}_{\text{relative}}) = -3.051 \log(1999 - \text{year}_{\text{ejection}}) + 4.633$$

- Under these conditions, the ZHR at stream center is given by:

$$\text{ZHR} = 2.94238 \times 10^6\ 10^{-3.051 \log(1999\text{-year of ejection}) + 4.633}$$

- Once ZHR and the distance, r, of the stream center are known, then the maximum observed ZHR for the stream is given by:

$$\text{ZHR}_{\text{obs}}(\text{ZHR}, r) := \text{ZHR} \cdot \exp\left[\frac{-428.467 r^2}{\left(10^{-0.29-0.35 \cdot \log(\text{ZHR})}\right)^2}\right]$$

Forecast Reliability

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Year	Stream Age	Model ZHR	Historical ZHRs Yeomans	Historical ZHRs Brown
1832	1666 1699	17900 15300	20000	2000
1833	1666 1699	9000 32500	50000	60000
1901	1733	450	?	250
1903		0	250	>200
1966	1899	90200	150000	80000-100000

Unable to reproduce/validate Asher ZHR numbers

Brown/Cooke Leonid Forecast

Date	Peak Time (UT)	Ejection Year	ZHR_{obs}
2000 Nov. 18	03:44	1733	500
	04:40	1767	125
2001 Nov. 18	10:01	1767	2250
	12:00	1799	11000
	14:36	1833	700
	16:50	1666	2200
	17:31	1699	2450

Brown 2000 ZHR Profile

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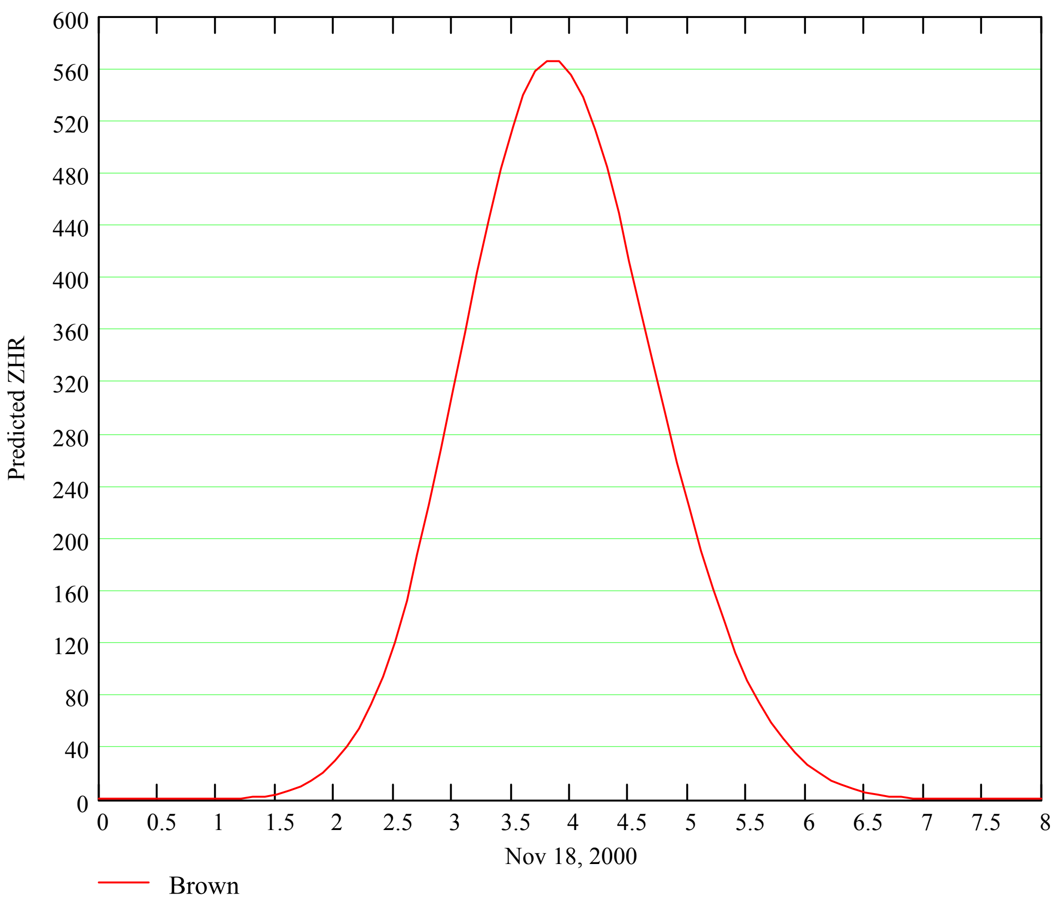

2000 GEO Profile

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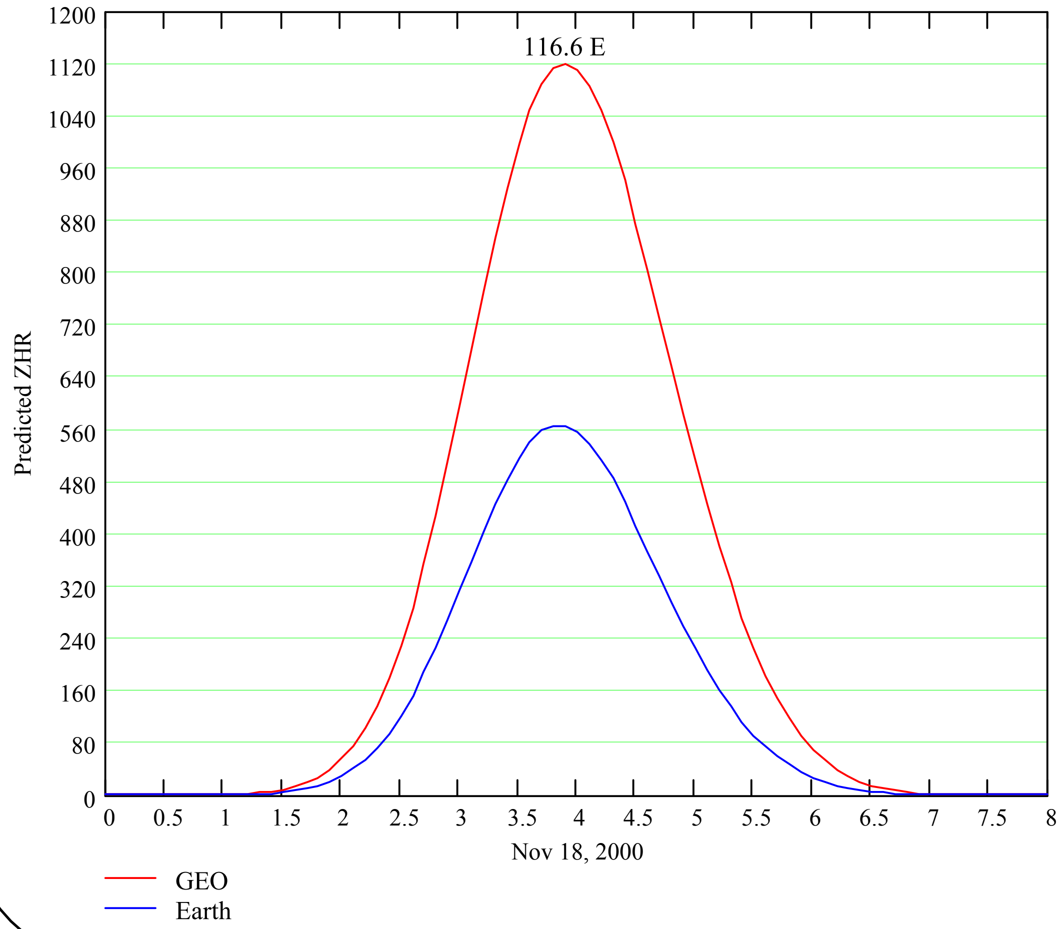

- At storm level for satellites located at longitudes 95 – 130 degrees E.
- Max flux ~0.4 km^{-2} hr^{-1}.

2001 Comparison

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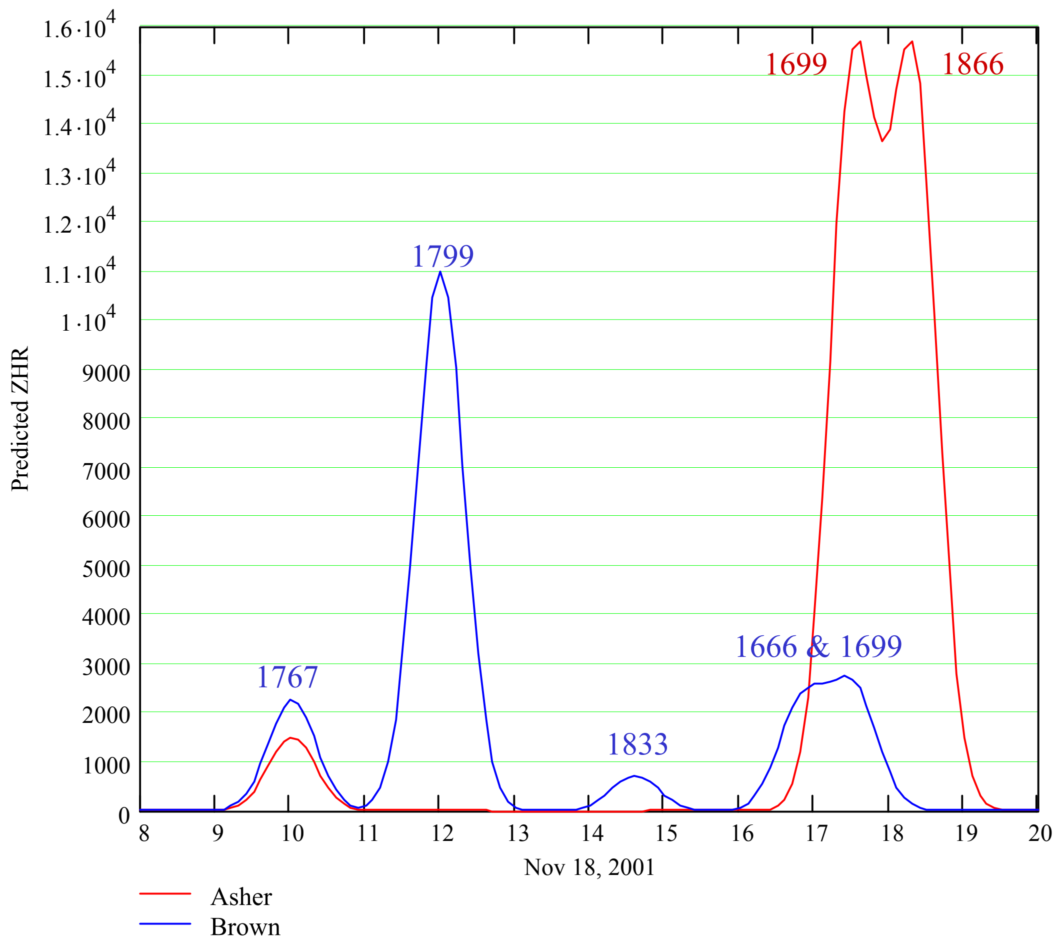

2001 GEO Profile

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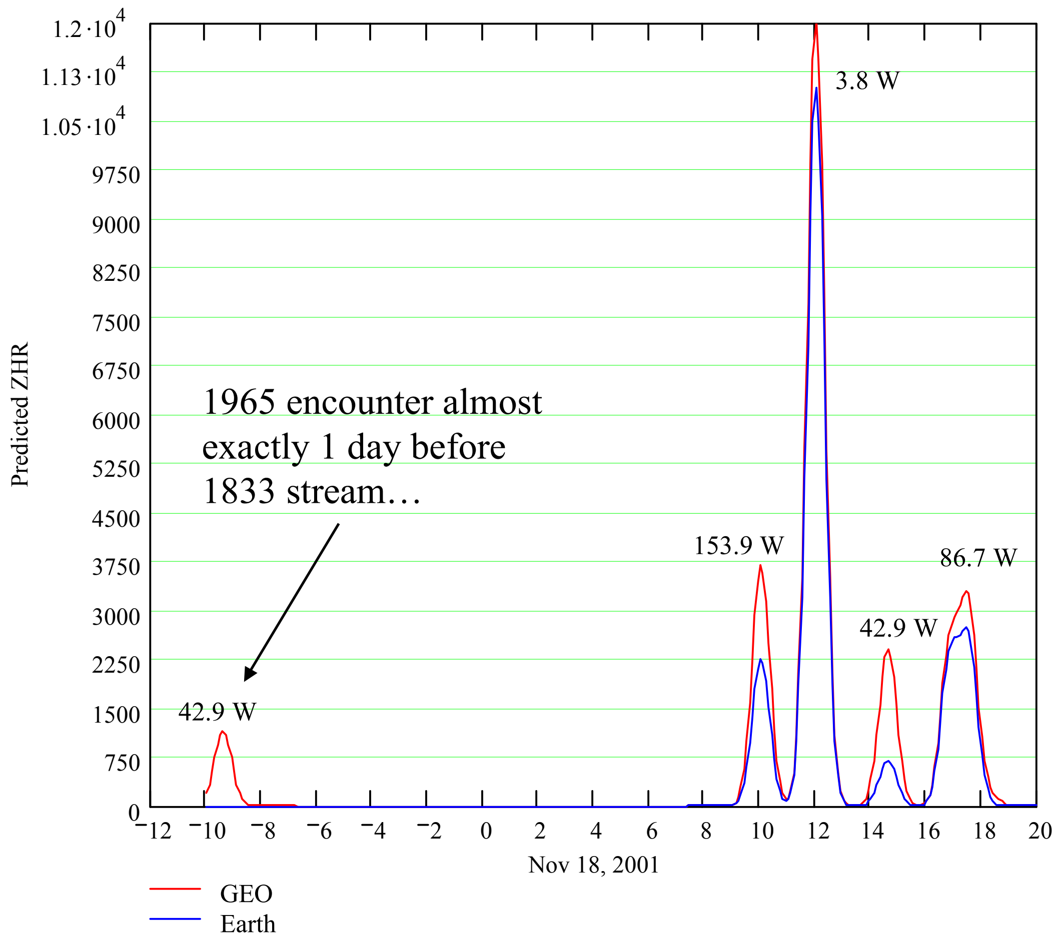

- GEO rates much higher for younger streams – 1965 makes an appearance.
- Most dangerous for satellites over Western Europe/Atlantic
- Max flux ~5 km^{-2} hr^{-1}.

2001 1799 Stream Encounter

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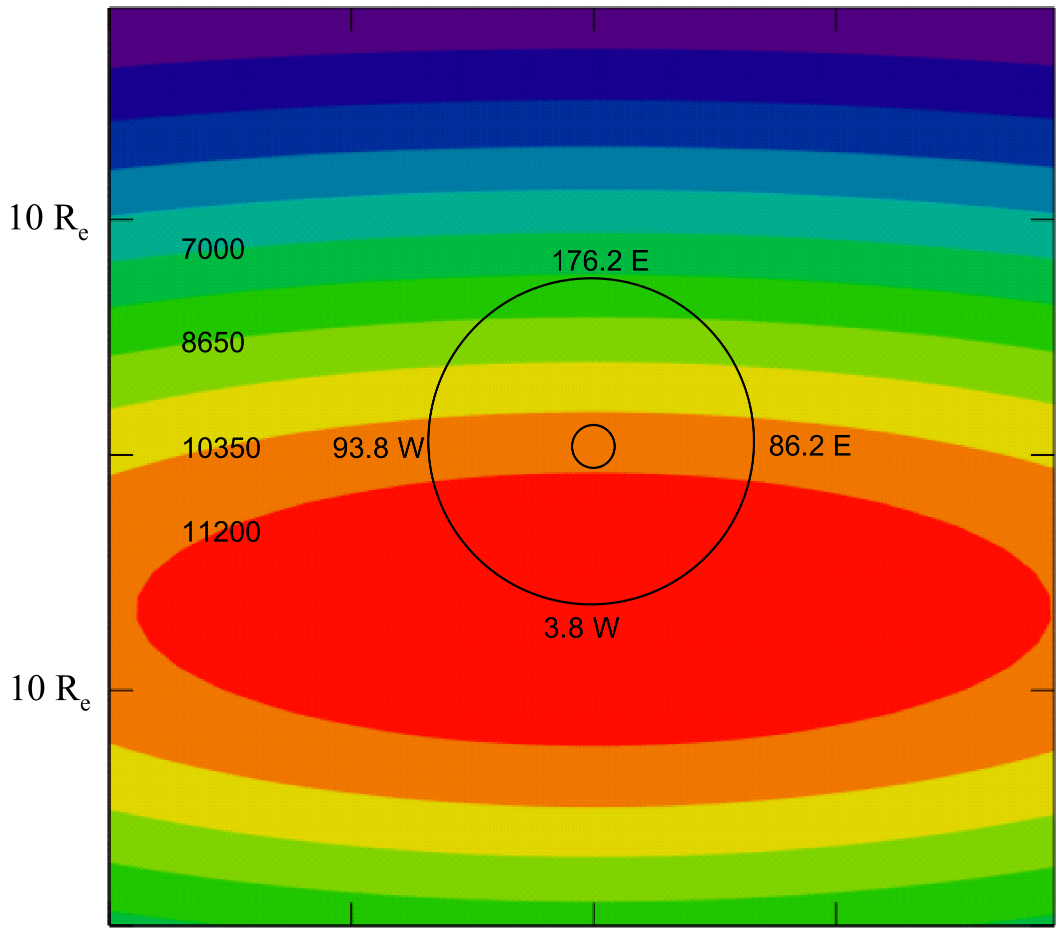

Numbers along contours near left side of graph give ZHRs at those positions.

Circle marks GEO distance.

This is an interpretation of Peter Brown's calculations – David Asher's results would look much different for the 1799 stream.

Asher 2002 ZHR profile

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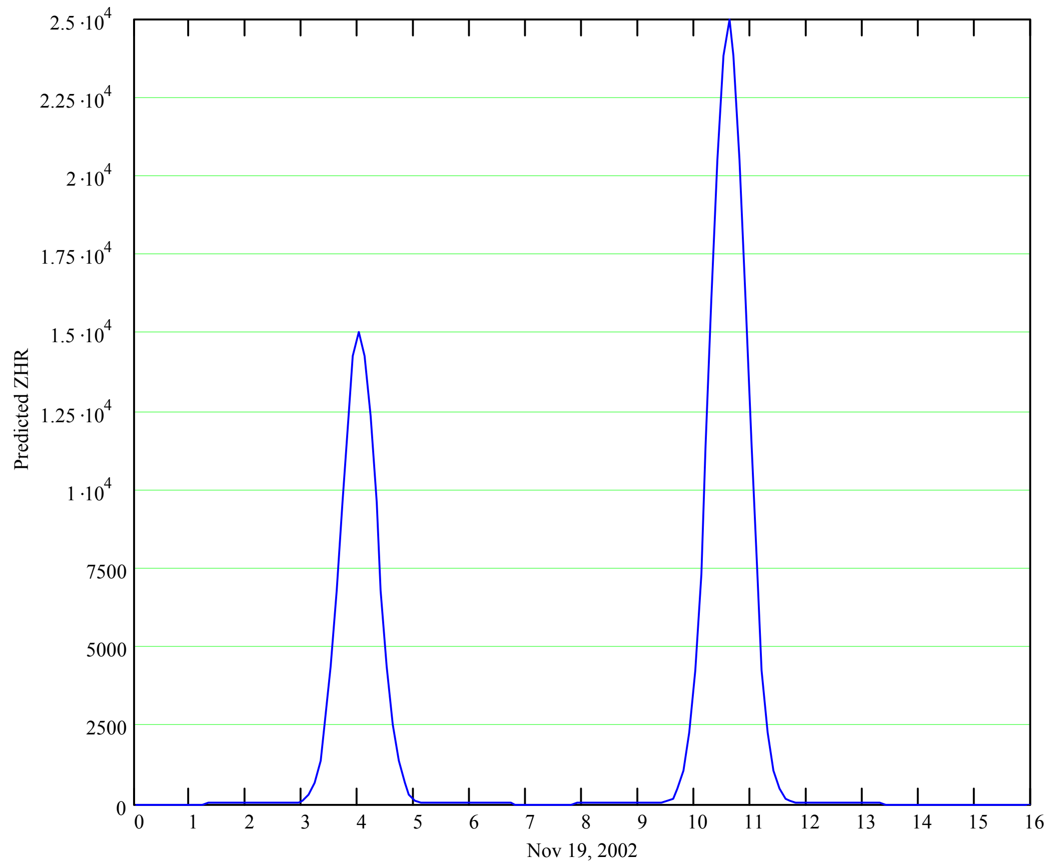

Model Summary

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- Both models predict normal or enhanced Leonid activity in 2000. This is in agreement with the low storm probability (0.25) given by historical study. Rate difference may help discriminate between models (also times of peaks, if any).
- Both models predict moderate Leonid storm (ZHR ~10,000) in 2001, though stream contributions (hence peak times) are different. High activity can be expected between 7 and 20 hours UT on November 18.
- Total fluence in 2001 currently predicted to be ~5-7 Leonids km^{-2}(LEO-GEO), which equates to about a 3-5% chance of someone's satellite being hit by a Leonid of 10 μg or larger. Fluence in 2000 projected to be ~0.4 Leonids km^{-2}.
- As of this time, no Brown calculations published for 2002. Asher predicts intense storm with rates as high as 25000. Historical data too sparse to say anything, save that the storm chance is > 0.3.

Other Relevant Factors

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- Preliminary light curve results from 1999 USAF/NASA ground campaign indicate that Leonids may be conglomerates of small grains, rather than little dusty snowballs.
  - Penetration equations probably not valid.
  - Plasma/current production potential?
  - ALTAIR observations, when reduced, should provide more information (decelerations ⇒ densities).
  - Spectra may also provide clues.
- According to Brown's 2001 numbers, the space earthward of L_2 should see a ZHR ranging from 8000 at L_2 to ~100,000 some 100,000 km distant. This will occur at approximately 17 hrs UT on November 17th of 2001. Asher's model yields similar results.
- L_1 should be unaffected by all streams back to 1666 – No calculations presented for older streams.

Recommendations

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- Low level observational effort in 2000 in attempt to discriminate between (or improve upon) Asher and Brown models. Low rates and moonlight will probably hamper optical observations, but high ZHR predictions for 2001 and 2002 dictate that some effort must be made.
- No near real-time monitoring for 2000. Expensive, and situational awareness, if desired, can be provided much more cheaply by a web site linked to a meteor radar.
- Satellite positions on November 18 of this year can be forwarded to ED44 for ZHR/flux evaluations.
- Both models underestimated 1999 activity. Given this, it would be reasonable for projects to adopt some sort of mitigation strategy for the 02 to 09 UT time frame on November 18th of this year.

Where Do We Go From Here?

- ED44 developing new-tech, low cost bistatic meteor radar, which differs from others in that meteor counts are not done via AGC, but rather by looking for signatures in an FFT. Work that needs to be done includes:
  - Develop and test automated counting software (ongoing)
  - Calibration of system (radiant angle, background meteor removal)
- Because the current dynamical models suffer from some non-physical assumptions or approximations, ED44 plans to develop a stream model that can be used to evaluate meteor storm hazards in Earth orbit (Chandra), at the Earth-Sun Lagrange points (NGST), and in interplanetary space (solar sails). It is thought that this will help produce better forecasts of shower intensities (flux) in future meteor stream encounters.

2000 Observational Effort

- Proposed 2000 observational effort involves use of IMO, meteor radars at MSFC and Canada, and deployment of existing electro-optical video equipment to ~4 sites in N. America – Canada, MSFC, JSC (Cloudcroft), ?.
- Amateur observations alone not sufficient because
  - Moonlight will impact visual observations more than video
    - Video enables post-shower analysis
    - Very few IMO members in USA
  - No light curve information, which is key to understanding composition
  - No photometric masses
  - No ability to specify requirements on deliverables in order to meet project needs
- Total cost: $75k (deployment, observation, data analysis)

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Backup Slides

Leonid Light Curve

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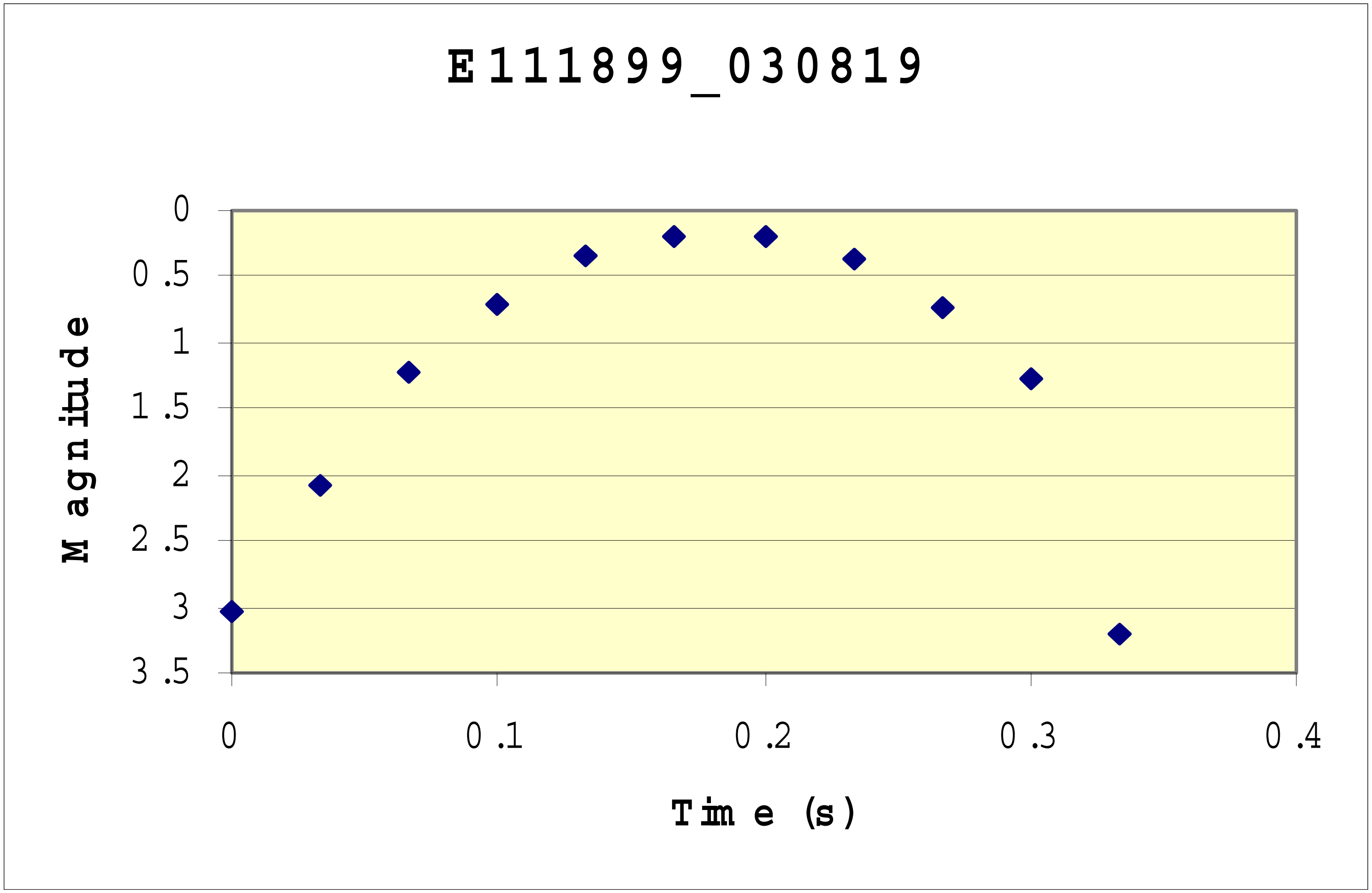

Video Flux Measurement

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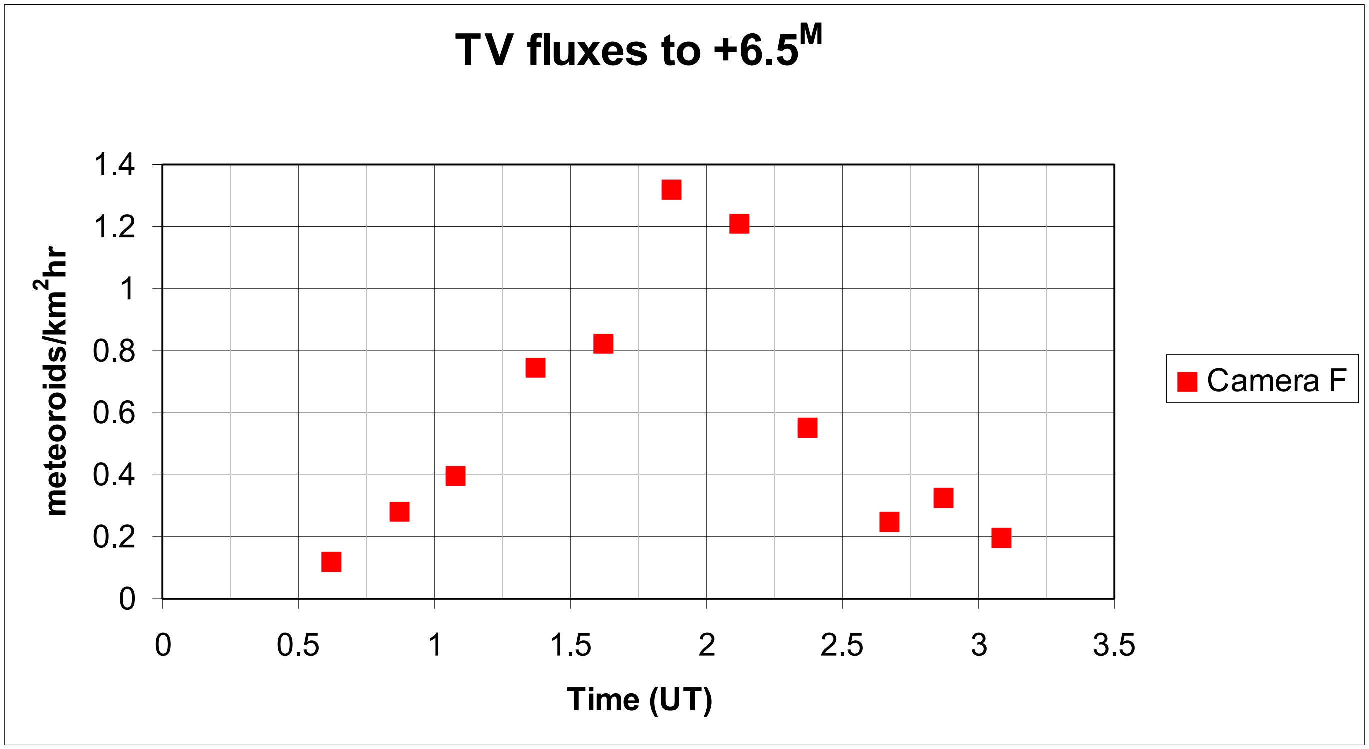

2000 Brown Forecast (a là Cooke)

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Ejection Year	$d_{average}$ (AU's)	ZHR
1666	-0.0046	1
1699	-0.0051	0
1733	-0.0019	506
1767	-0.0022	126
1799	-0.0026	4
1833	-0.0032	0
1866	-0.0034	0
1899	0.0053	0
1932	0.0018	0
1965	-0.0018	0

GEO distance ~ 0.00028 AU

Negative $d_{average}$ means stream is inside Earth's orbit

2001 Brown Forecast (a là Cooke)

Ejection Year	$d_{average}$ (AU's)	ZHR
1666	-0.0006	2200
1699	-0.0008	2450
1733	0.0044	0
1767	0.0012	2250
1799	-0.00028	11000
1833	-0.0014	700
1866	-0.0017	10
1899	0.0093	0
1932	0.0047	0
1965	-0.0007	0

GEO distance ~ 0.00028 AU

Negative $d_{average}$ means stream is inside Earth's orbit